RADIO OBSERVATIONS DURING THE CASSINI FLYBY OF JUPITER

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Abstract

On December 30, 2000, the Cassini spacecraft, en route to Saturn, made its closest approach to Jupiter at a distance of 137 Jovian radii. Actually, the radio astronomy instrument (RPWS) aboard Cassini detected Jupiter as far back as October 25, 1998, immediately after the deployment of its three, 10 meter long wire antennas. Systematic observations of Jovian radio emissions started in February 2000, from a distance of about 2.1 AU, and continued in 2001, for several months after Jupiter's flyby. During the whole period, the most comprehensive survey of Jovian radio emissions was performed to date, by using unique capabilities of the RPWS instrument. Namely: i) very sensitive radio receiver (HFR) in an acceptably clean RFI environment; ii) wide–band spectral analysis from a few Hz up to 16 MHz leading to almost complete coverage of Jupiter's radio spectrum; iii) high spectral resolution both in time and frequency (down to 1 millisecond and 100 Hz respectively); iv) full analysis of the polarization of received waves. In addition, the Cassini measurements could be strengthened by several other radio astronomy instruments, operated at the same time to provide us a multiple, "stereoscopic" view of Jupiter. They included several other spacecraft/wave experiments in space: Galileo/PWS - in orbit around Jupiter -, Ulysses/URAP - passing over the Solar South Pole in late 2000 -, Wind/WAVES - nearby the Earth -, and, on the ground, several powerful radio telescopes like those in Nançay (France) or Kharkov (Ukraine). Some results to date and research in progress are outlined, as well as the consequences of new observational facts for our understanding of the Jovian magnetospheric physics.

1 Introduction

In situ exploration of Jupiter environment began in 1974 with flybys of Pioneer spacecraft, which did not carry any wave instrumentation, but could give the first description of the large scale properties of the Jovian magnetosphere. Dedicated radio astronomy experiments, aboard Voyager 1 and 2 (1979) and Ulysses spacecraft (1992), provided a wealth of data and detailed descriptions of new phenomena, thus widely extending our knowledge

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of the Jovian magnetosphere properties. Relationships between radio emissions, auroral particles energetics and satellite orbital motions were further demonstrated thanks to the Galileo spacecraft, in orbit around Jupiter since 1995.

Initially planned as a gravity assist to the interplanetary path of Cassini spacecraft en route to Saturn, the swing by of Jupiter, at the end of the year 2000, provided a spectacular occasion of getting a renewed, close vision of the giant planet, and offered a unique opportunity for simultaneous studies by using several other available observatories at different places in the Solar System.

In this paper, one will mainly focus on the observations of Jupiter, carried out at radio wavelength by Cassini, along the whole year 2000 and in early 2001. In section 2, relevant new capabilities of the Cassini Radio and Plasma Wave Science (RPWS) investigation are described. Then, in section 3 some preliminary results and research in progress will be summarized.

2 New radio astronomy capabilities with Cassini: the RPWS investigation

2.1 Cassini mission overview

The Cassini mission was launched on October 15, 1997 at destination of the planet Saturn. The arrival at Saturn is planned for mid 2004, the main vehicle being put into orbit around Saturn for three years, and the atmospheric ESA Huygens probe being released into the atmosphere of Titan. To achieve this long journey within a reasonable launch energy budget, a complicated, interplanetary trajectory was designed, requiring gravitational assistance through several swing by of Venus (twice on April 26, 1998 and June 24, 1999), of the Earth (on August 18, 1999) and, finally, of Jupiter (on December 30, 2000). The Jupiter closest approach occurred at a relatively far distance of 137 Jovian radii, leading Cassini spacecraft to just enter the external dusk side boundary of the Jovian magnetosphere [Kurth et al., 2001d]. Nevertheless, all remotely capable Cassini instruments, including visible imaging (ISS), magnetospheric imaging (MIMI) and radio astronomy (RPWS), were activated and could provide a wealth of data. The Jupiter observing phase of the mission began in February 2000, at a distance of 2.1 AU from the planet, and is planned to continue until end of March 2001. However, because of the excellent sensitivity of the RPWS instrument, Jupiter radio emission was detected much earlier (Figure 1), namely immediately after radio astronomy antennas deployment when Cassini still was in the vicinity of the Earth.

2.2 RPWS instrument

2.2.1 Overview

The radio and plasma wave investigation (RPWS) aboard the Cassini spacecraft is designed to study radio emissions, plasma waves, and thermal plasma in the vicinity of

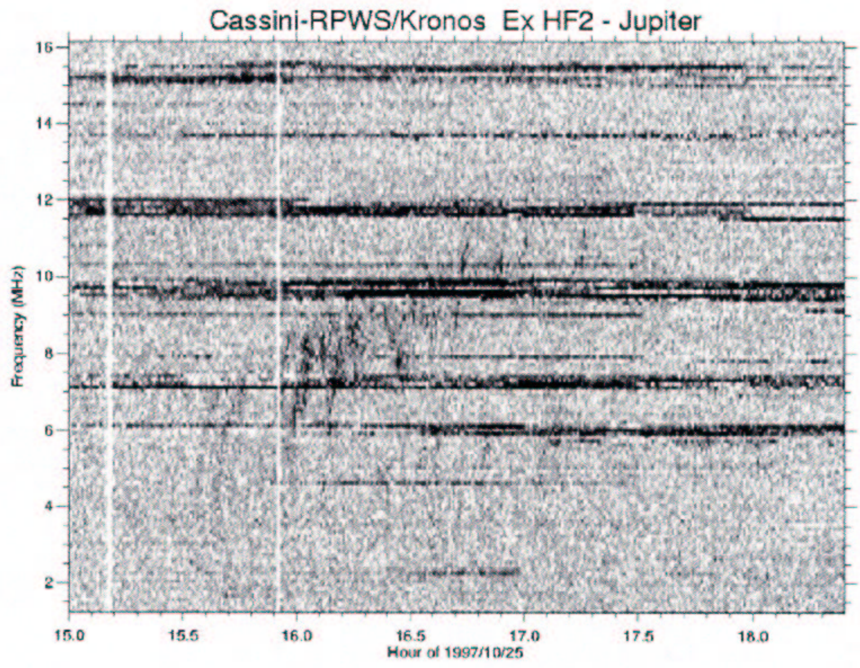

Figure 1: Jupiter first detection event on November 25, 1997. This spectrogram shows Jovian decametric arcs between about 4 and 11 MHz as seen by the Cassini RPWS high frequency receiver just after its antenna deployment. The basic structures are arc–like, appearing somewhat like parentheses in this display. The narrow–band fixed–frequency (horizontal) bands near 6, 7.3, 9.5, 12, and 15.3 MHz are short wave, man made radio emissions originating at Earth.

Saturn [Gurnett et al., 2001b]. It uses several electric and magnetic sensors and a Langmuir probe, for measuring electromagnetic waves as well as for studying in situ plasma waves and electron density. The signal analysis from the various sensors is performed by a set of spectrum and wave form analyzers, which provide high resolution spectral measurements of electric (resp. magnetic) fields over the frequency range from DC to 16 MHz (resp. 80 kHz). The analyzed signals are further delivered to the data processing unit which control all instrument functions and handle communications with the spacecraft. Dedicated software is used to enhance the scientific return of the instrument by performing various analysis and data compression operations.

2.2.2 High frequency receiver

During the Jupiter 2000–2001 swing by, the radio frequency part of the instrument (HFR) was mainly and heavily used for remote Jupiter studies, while the other sub–systems could perform in cruise Solar wind studies and measurements of the Jovian magnetosphere boundary during a few days near the closest approach.

The HFR enables the analysis of incoming electromagnetic waves over a frequency range from 3.5 kHz to 16.1 MHz, by combining output from three nearly orthogonal, 10 m long

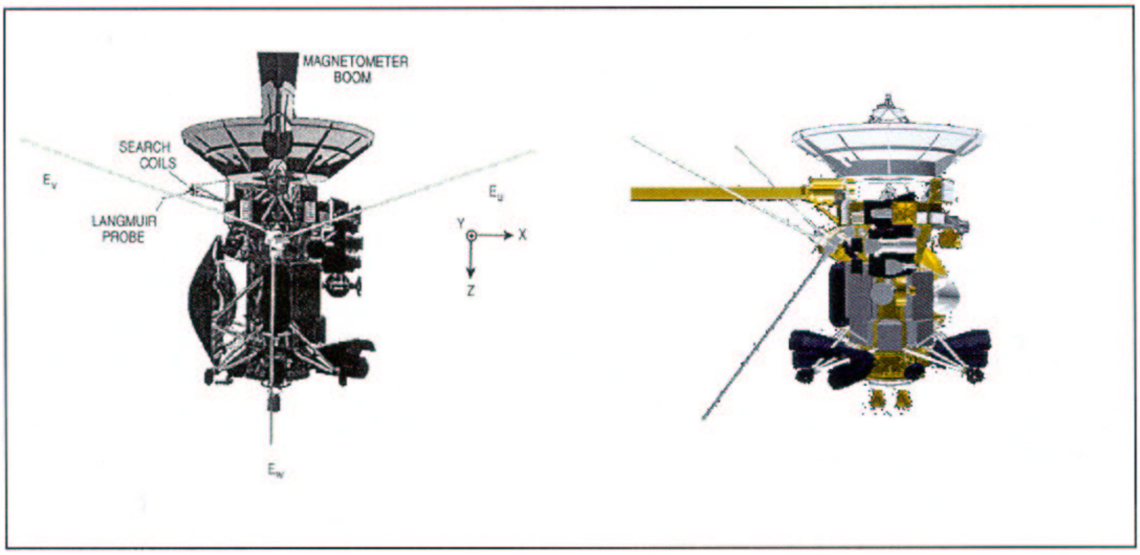

Figure 2: Drawing showing the RPWS antenna configuration, with respect to the Cassini spacecraft body and its main appendages (note the magnetometer boom and the Huygens probe).

monopole wire antennas erected on the spacecraft body (Figure 2). The entire spectrum is analyzed by using four distinct band pass filters, namely of width 3.5–16 kHz, 16–71 kHz, 71–319 kHz and 50–75 kHz. The latter filter can be tuned or swept by steps of 25 kHz everywhere in the spectrum. In each band, the spectral analysis is performed in two successive - analogue, then digital - stages. The analogue stage includes low noise amplification, filtering, frequency translation (if any), automatic gain control (AGC, over a 80 dB dynamic range). The filtered band, simultaneously measured by a pair of antennas, is further analyzed by the HFR on board digital processor, which can compute auto and cross correlations of the two input signals, over a selectable number of sub–frequencies (1 to 32), with an additional dynamic range of about 40 dB. The time resolution of each fixed frequency bands can be chosen between 0.125 and 1 s, while the tunable band has selectable resolution from 10 to 80 ms. The effective time resolution of one spectrum scan is defined by the chosen time resolutions and by the number of explored frequencies, mainly limited by the available data output bandwidth.

This very flexible scheme allows one to adapt the analysis to various observing situations, going from low bit rate survey up to high speed reconstruction of direction of arrival and full polarization of incoming waves.

2.2.3 HFR direction finding and polarization capability

For low frequency space borne radio measurements, technical constraints imply the use of very simple wire antennas, usually short compared to the wavelength, so that angular resolution is inaccessible to simple power measurement by a single antenna. However, information on direction of arrival and polarization of the wave is entirely contained in the second order average properties (wave coherency matrix) of the incident electromagnetic field. Previous space radio astronomy experiments aboard spinning spacecraft as RAE, ISEE–3 or Ulysses, have used rotating antennas and simple quadratic detection scheme for retrieving these properties: it can indeed be shown [Lecacheux, 1978] that sampling of the power output of a single rotating antenna is equivalent to computing the correlation product from two orthogonal antennas lying in the spin plane, as far as properties of the wave are steady at the spin period time scale. Since Cassini spacecraft is 3–axis stabilized, this was not possible and full correlation scheme must be implemented. The RPWS/HFR subsystem can measure the coherency matrix of the incident electromagnetic field, by simultaneously using a pair of antennas and digitally computing the auto and cross correlation products of the digitized instantaneous voltages. To achieve full polarization determination, two different pairs of antennas can be used, alternatively, among the three available monopoles antennas. In practice, application of this method requires the accurate knowledge of effective heights (length and direction) of the electric dipoles equivalent to the physical monopole antennas. The actual effective heights depend on the shape of the various booms erected on the spacecraft body and on the whole current distribution on the spacecraft in flight, and, therefore, cannot be determined a priori. Two different methods were used to calibrate the RPWS electric antennas. The rheographic method was first used before launch [Rucker et al., 1996]: electrical receiving properties of the antennas are measured with a spacecraft rotating scale model immersed in a water tank, in which a uniform electric field is applied. A second method consists in doing the full direction finding analysis in flight, but by using a radiosource whose direction and polarization properties are already known: the antenna parameters can then be retrieved by inversion [Ladreiter, 1995]. A part of Jupiter observing plan was devoted to this activity, both on inbound and outbound trajectory to Jupiter, by using several scheduled special spacecraft maneuvers (full spacecraft slow rolls around chosen axes). An example of in flight antenna calibration measurements is given in Figure 3.

2.2.4 Calibrations et performance

The HFR was designed to achieve the maximum sensitivity over the 120 dB dynamic range needed for studying all the highly intensity varying electromagnetic phenomena expected to be observed in the magnetosphere of Saturn. The HFR response curve is plotted in Figure 4, before and after deployment in flight of the antennas. The intrinsic noise level is lower than $5 \cdot 10^{-17}$ V^2/Hz and 10^{-16} V^2/Hz for the fixed and tunable frequency bands respectively, so that actual sensitivity is only limited by the galactic background level for all frequencies above a few 100 kHz.

3 Observations at Jupiter and some first results

3.1 Jovian radio emissions "family portrait"

Figure 5 displays an example of overview of the various components known in Jovian radio spectrum, from 3.5 kHz to 16 MHz. One can recognize the two (Io and non Io–

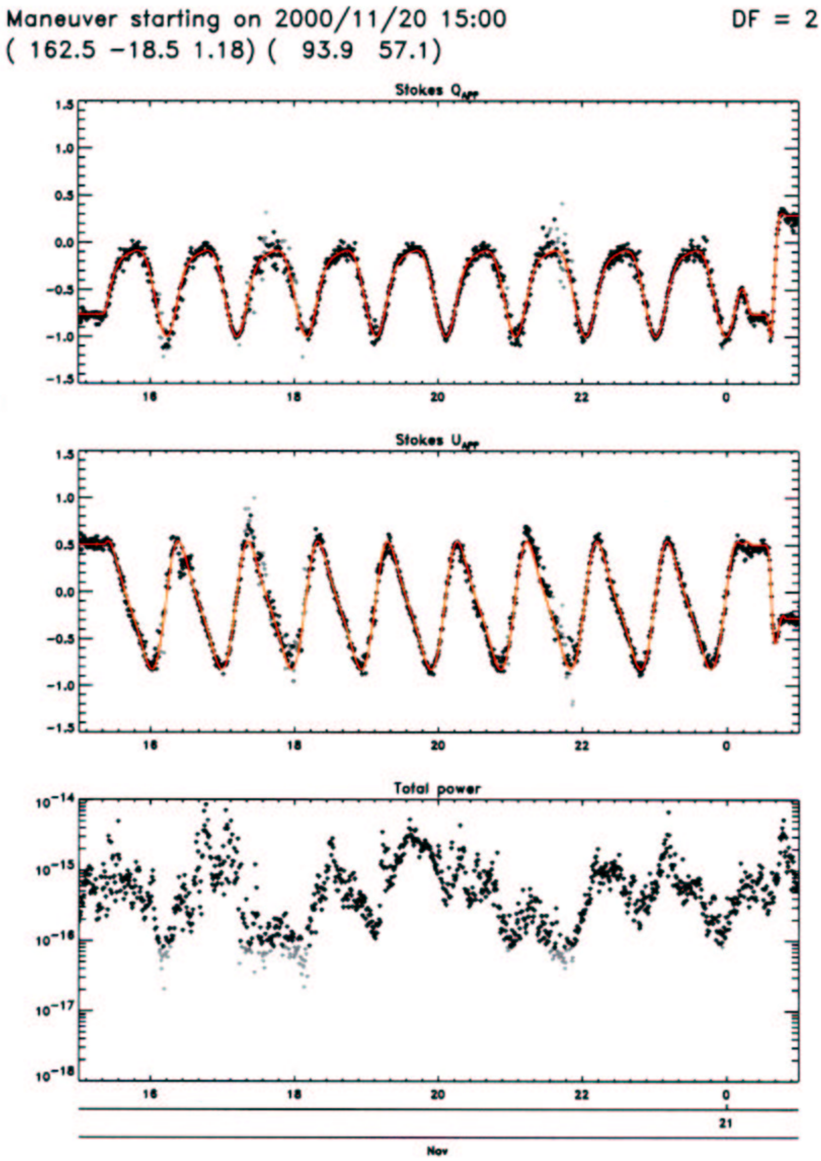

Figure 3: Analysis of the RPWS antenna calibration maneuver on November 20, 2000. The maneuver consists in nine successive slow rolls (about one cycle per hour) around the spacecraft Y–axis. The lower panel displays the rapidly variable, Jupiter signal intensity, most of the time well above the sky background level. The two upper panels display the variation of two normalized parameters describing the antenna response to the Jupiter signal (namely the apparent Q and U antenna Stokes parameters). The observed parameter variations (dots) can be fitted to the best antenna model (red curve) with an excellent precision [Lecacheux, 2001, in preparation].

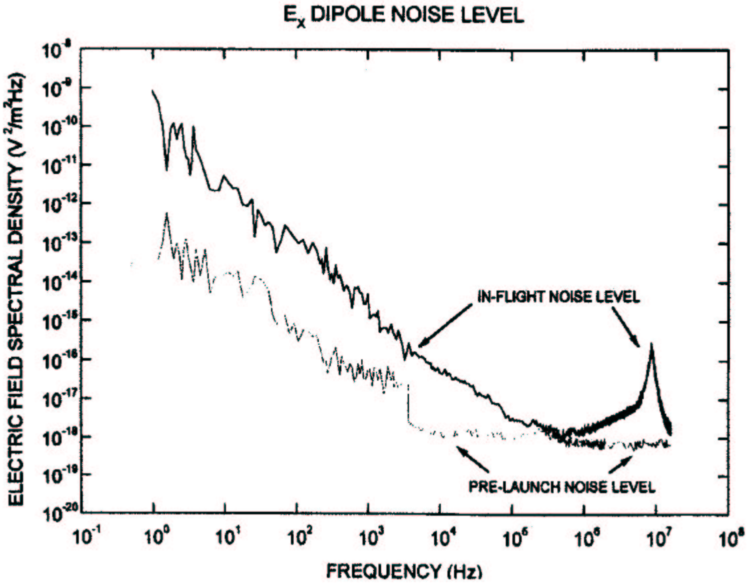

Figure 4: HFR noise spectrum: plots of the pre–launch and in–flight background noise level for the dipole configuration. The enhanced in flight noise levels at low frequencies is due to the thermal plasma around the antenna. The enhanced in flight noise levels above a few 100 kHz is due to the galactic background; Note the half wave antenna resonance at about 9 MHz.

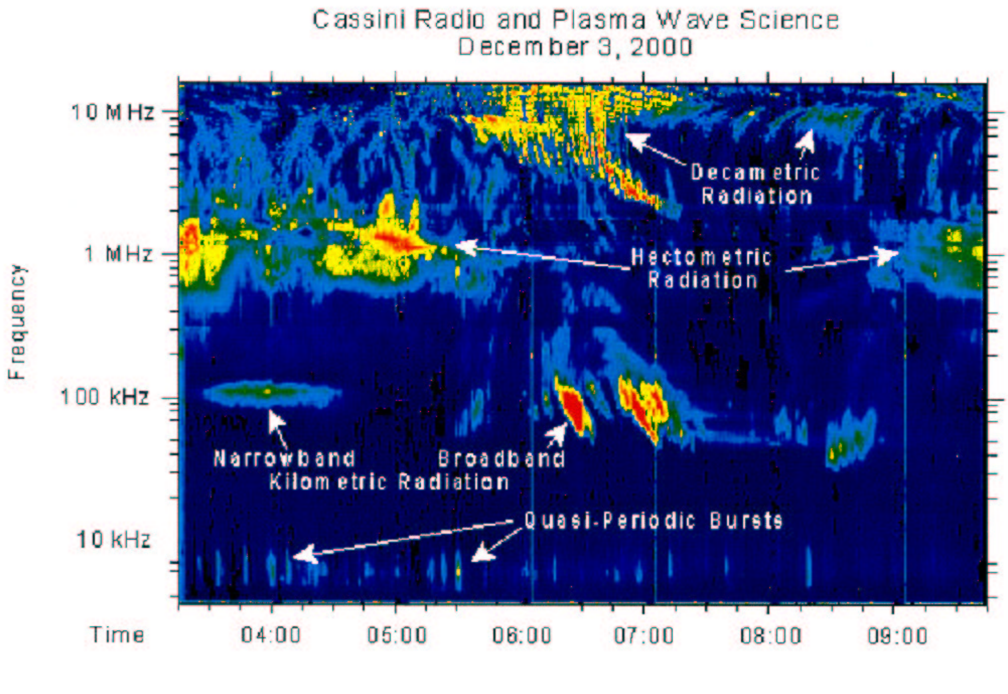

Figure 5: Synthetic view of RPWS data obtained in early December, 2000, showing all the main phenomenological components (”family portrait”) of Jupiter radio emissions.

controlled) decametric DAM components, both exhibiting characteristic, "arc" shaped intensity modulation; the hectometric (HOM) components that likely is the continuation of non Io DAM towards lower frequency; the "narrow–band" (nKOM) and "broad–band" (bKOM) kilometric components. All these components are known to originate from Jovian auroral regions, except the nKOM which is associated to plasma structures on the outer flank of the Io plasma torus. The "Quasi Periodic bursts" (QP), whose origin is still uncertain, are also well noticeable in the lowest frequency range (< 10 kHz). For a review of the phenomenology and related theories, see Zarka [1998].

Obtained quasi continuously during more than one year, these data constitute the most comprehensive, broad–band survey of Jovian radio emissions to date. Indeed, ground–based observations are more or less limited to the upper part of the spectrum (> 10 MHz), because of radio wave shielding by the terrestrial ionosphere; on the other hand, the famous data set obtained by the Planetary Radio Astronomy instrument aboard Voyager 1 and 2 was also practically limited to the frequency range below 1.4 MHz, because of instrumental sensitivity reasons (limitation due to onboard RFI), excepted during a few weeks around Jupiter closest approach.

3.2 Direction finding: 2D–imaging and polarization

Figure 6 displays a test example of the direction finding (DF) analysis capability of RPWS experiment. The data used cover an interval of about one day after the periapsis, when Cassini was in average at 139 Jovian radii from Jupiter. At the chosen frequency (1025 kHz), Jupiter was active most of the time. The direction finding analysis was carried out for each data sample (one every about 10 seconds), following the scheme described in the previous section, assuming a point source model with only circular polarization. The arrival directions of each circularly polarized components were calculated, then averaged over the whole time interval and displayed as a 2D image in front of the sky plane. The obtained image clearly shows, as expected, two distinct, radio sources, associated with Jovian Northern and Southern poles, in opposite senses of circular polarization. The extended patches of obtained directions are partly due to intrinsic DF measurement accuracy, mainly limited by signal contrast above the background; but are also consistent with geometrical extent of high latitude 1025 kHz radio source radiating at the electron gyro frequency altitude.

Figure 7 is another example of DF computation, aiming to the determination of Jovian DAM polarization over the whole dynamic spectrum. This kind of display clearly disentangle dynamic spectral features belonging to each polarization component, therefore helping for better understanding the dynamical relationship between Jovian auroras occurring in northern and southern hemispheres.

3.3 Jupiter stereoscopic studies

A long living, outstanding problem in planetary radio physics is the description of the instantaneous radiation beam, and its confrontation with theory. While indirect, statistical analyses of Jovian DAM (ground–based) observations, accumulated over the past

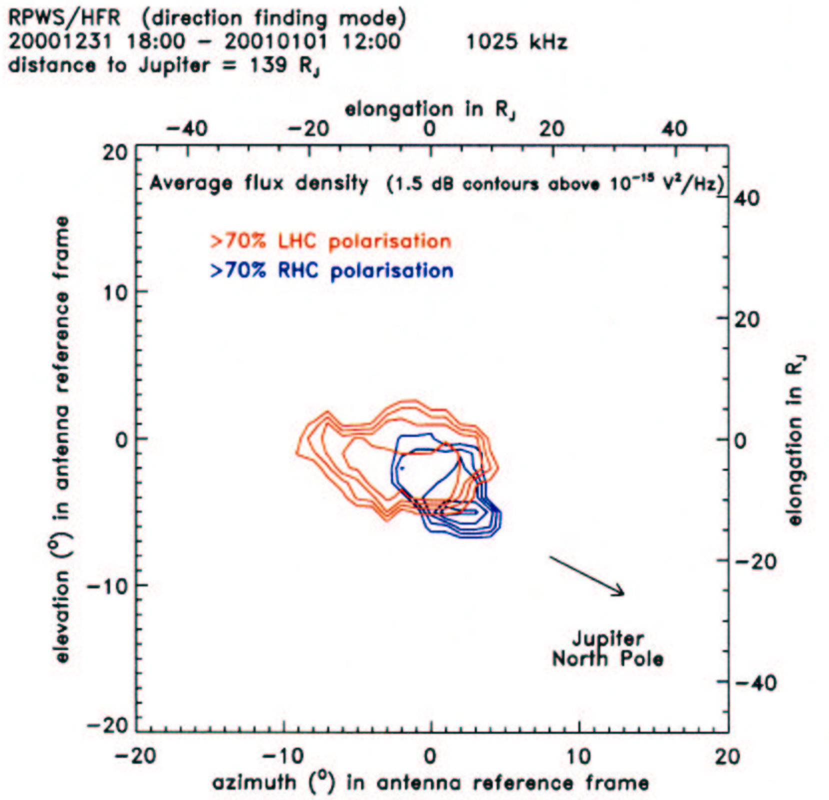

Figure 6: 2D–imaging of Jupiter radio source at 1025 kHz, as viewed by Cassini RPWS from a distance of 139 R_J. The blue (resp. red) isocontours delineate the apparent average brightness of right hand (resp. left hand) circularly polarized emissions, linked to the Northern (resp. Southern) magnetic hemispheres of Jupiter.

forty years, have led to a quite oversimplified description by assuming a thin, hollow cone model, only very few stereoscopic observations are available before Cassini, in order to try to validate or improve this model. For instance, it is still unclear if the characteristic spectral features of Jovian DAM (arcs, etc...) result from the complex beam of one localized radio source, or if they are due to elementary beams from successively visible, multiple sources. The curvature itself of the arc shaped structures is not easily explained, even by taking into account the Jovian magnetic field geometry. These basic uncertainties have made difficult any study of the relationship of radio emissions with visible and UV auroras.

At the time of Cassini encounter with Jupiter, a number of other observatories, in space or ground–based, were fortunately available for direct comparisons and, even, for "stereoscopic" radio measurements, i.e. simultaneously obtained from two or more, significantly different directions.

Figure 8 shows in a jovigraphical reference frame centered at Jupiter (JSE coordinates) the positions of these radio observatories, including Cassini. They were Galileo (and PWS instrument), in orbit around Jupiter and moving in and out its magnetosphere;

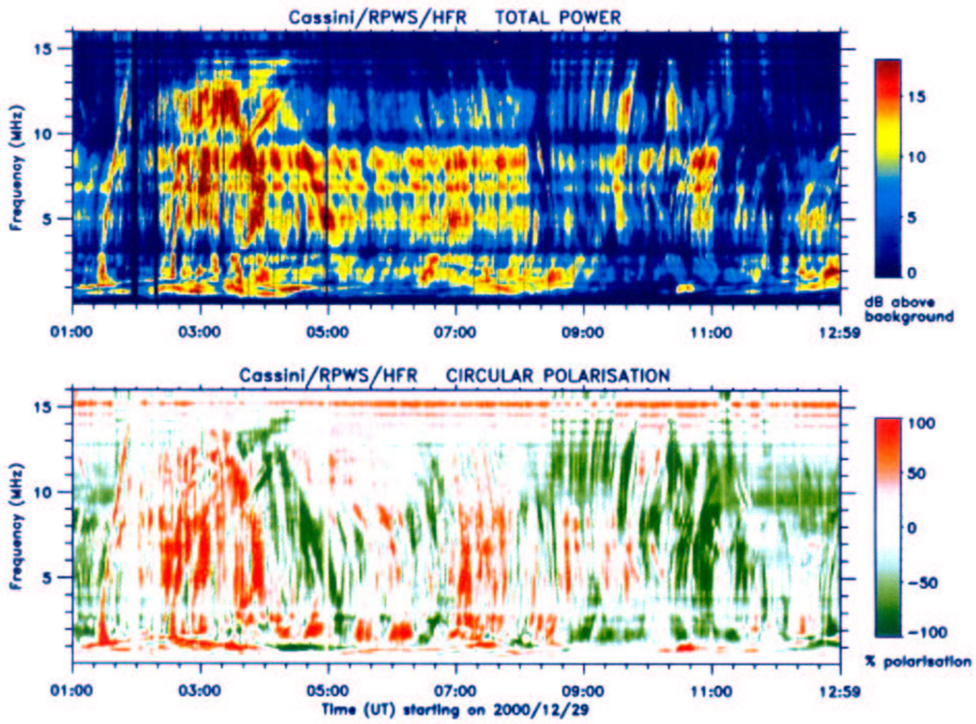

Figure 7: Dynamic spectrum of Jovian DAM radiation in total power (top) and degree of circular polarization (bottom), after application of direction finding algorithm to the RPWS data.

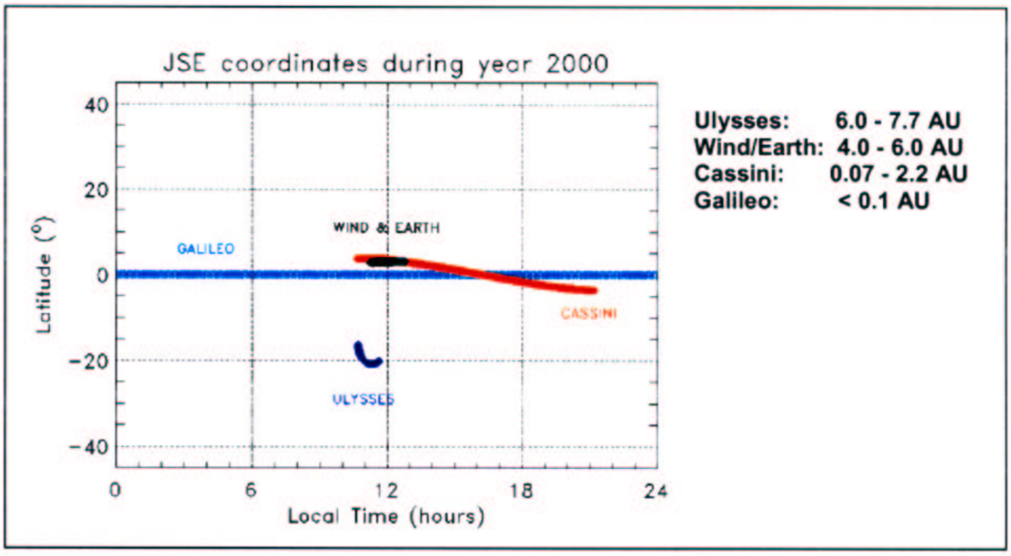

Figure 8: Jovigraphic map of positions of the "available" radio astronomy spacecraft at the epoch of Cassini–Jupiter encounter.

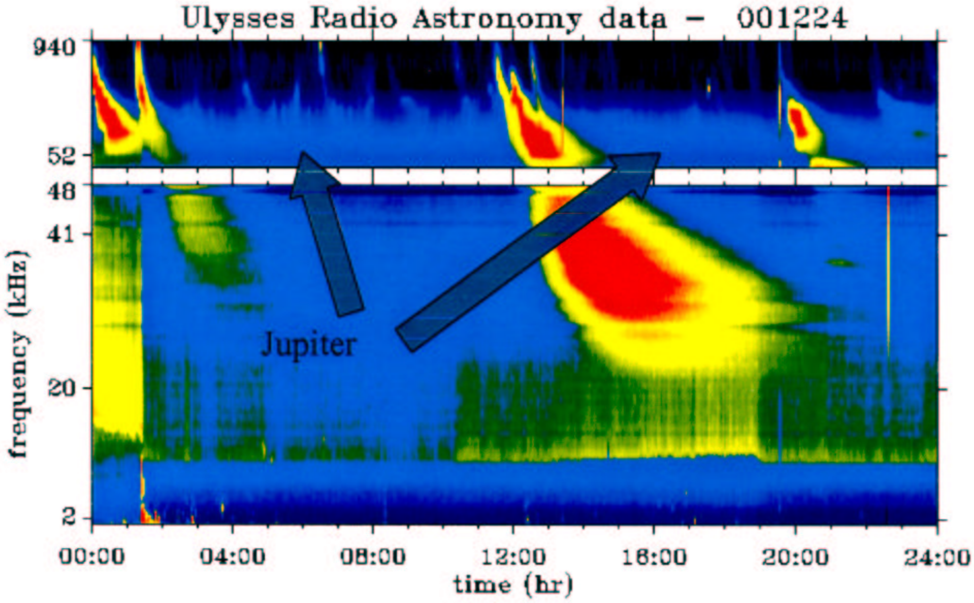

Figure 9: Example of Ulysses/URAP observation showing faint Jupiter emissions at kilometric frequencies.

Ulysses (and URAP instrument), passing over the Solar South Pole in late 2000, but able to monitor Jovian radiation out of the equator plane; Wind (and WAVES instrument), nearby the earth, but allowing simultaneous studies of low frequency DAM radiation; and finally, ground–based on the earth, several powerful radio telescopes like those in Nançay (France) or Kharkov (Ukraine).

3.3.1 By using other spacecraft

Figure 9 is an example of contemporaneous observation of Jupiter bKOM emission by Ulysses (URAP) at a distance of about 7 AU from the planet. A detailed study of such data should allow to get a better understanding of the beaming in latitude of Jovian radiation [Barrow et al., 2001a].

By using Wind spacecraft (WAVES), Kaiser et al. [2000] could carry out a first direct stereoscopic analysis of the DAM beam width, by using 1999 data, while Cassini and Wind directions differed by less than 5° (in CML, after correction for light time). The authors main conclusions are that the hollow cone width is as small as $1.5° \pm 0.5°$ and that the conical beam moves at Io's revolution rate in the case of Io–controlled arcs. By using more recent data, same kind of comparison might be fruitfully repeated and extended to much larger separation angle.

3.3.2 With ground–based observatories

Stereoscopic comparison of Cassini data with a ground–based radio telescope like the Decameter Array in Nançay (France) is, in principle, fairly easy since such a telescope easily compensates the sensitivity loss, due to distance effect, by a much larger antenna sensitivity. In the case of Nançay array, comparable signal levels are indeed obtained at Cassini distance from Jupiter of about 0.1 AU. In practice, the task is a bit more difficult because ground–based observations are done only part of the day and, mainly, because the actual sensitivity can be quite reduced by strong, man made RF interference, at frequencies below 20 MHz.

An example of such a comparison is displayed in Figure 10. An intense Io–B event could simultaneously be recorded at about 16 UT on February 27, 2000. The distance difference was 3.45 AU corresponding to 28.7 min of light travel time. The Cassini - Nançay CML (resp. Io phase) difference was 11.5° (resp. -1.8°). The figure indicates that the event occurred at different UT times and CML longitudes at Cassini and Nançay, but for the same Io phase. This result directly demonstrates that the Io–controlled radiation beam is likely tied to the Io flux tube when Io rotates, and confirms earlier findings. An additional and interesting result is that the observed radiation should consist in a fairly steady beam, since recorded signals at both locations look quite similar both in time and frequency, while they correspond to emission times about 13 min apart and Io flux tube feet locations some 1000 km apart.

3.4 Jovian magnetosphere dynamics

From remote radio measurements, in particular by using Galileo [Louarn et al., 1998] as well as from in situ particle measurements, it has been established that large dynamical changes occur in Jovian magnetosphere on time scales ranging from day to weeks. The extent to which these changes occur in response to the Solar wind pressure variation remained to be investigated. By studying radio measurements, Solar wind magnetic field and plasma measurements and auroral optical measurements simultaneously carried out by Galileo and Cassini spacecraft during the Jupiter flyby, Gurnett et al. [2001a] suggest that a relationship may exist between bursts of hectometric (HOM) radio emission, auroral EUV emissions and interplanetary shocks which could play the role of triggers.

4 Summary

This short (and maybe premature) review is inevitably incomplete and has certainly omitted to report on several important results or research in progress. However, it is clear that the "remote" fly by of Jupiter by Cassini in December 2000 was an excellent opportunity for the understanding of the magnetospheric processes in general and the case of Jupiter in particular. The Radio and Plasma Wave investigation new instrumental concepts were successfully validated. New insights on properties of planetary radiations were obtained and are presently under study. The next step for the Cassini mission is now its main target, the planet Saturn.

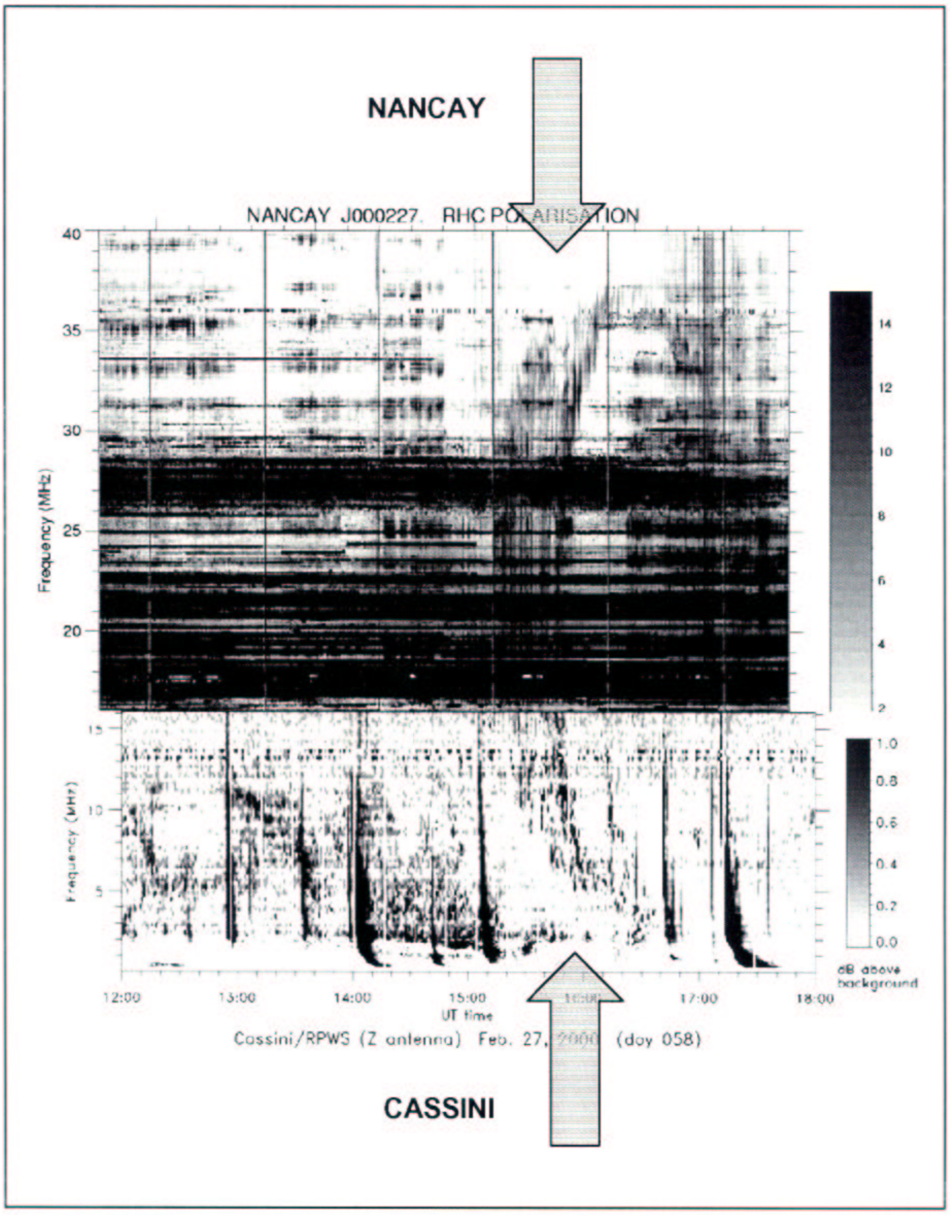

Figure 10: Composite dynamic spectrum obtained on February 27, 2000 from Cassini/RPWS, between 1 and 16 MHz (bottom), and Nançay Decameter array, between 16 and 40 MHz (top). The time axis is aligned in Io phase. The heavy horizontal black patches in Nançay data are due to strong RF interference; vertical streaks (one hour interval) correspond to periodic gain calibration of the instrument. By looking at both grey shade color bars, note the difference in sensitivity between the two instruments (the Jupiter signal being at least 20 times stronger in Nançay data), which has been compensated here by image processing technique.

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